

Exotic hadrons and SU(3) chiral dynamics

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Abstract

We explore a possibility to generate exotic hadrons dynamically in the scattering of hadrons. The s -wave scattering amplitude of an arbitrary hadron with the Nambu-Goldstone boson is constructed so as to satisfy the unitarity condition and the chiral low energy theorem. We find that the chiral interaction for the exotic channels is in most cases repulsive, and that the strength of the possible attractive interaction is uniquely determined. We show that the attractive interaction in exotic channels is not strong enough to generate a bound state, while the interaction in nonexotic channel generate bound states which are considered to be the origin of some resonances observed in nature.

Strong interaction of QCD exhibits rich spectra of hadrons in the non-perturbative vacuum at low energy, where about 300 hadronic states have been observed [1]. It is important to investigate the properties of hadrons to understand the low energy dynamics of QCD. Chiral symmetry provides us a way to study hadron properties in connection with the fundamental theory of QCD.

Dynamical models based on chiral symmetry, known as chiral unitary approach, successfully describe the two-body scattering of hadrons with the Nambu-Goldstone (NG) bosons in coupled channels, dynamically generating some s -wave resonances in the scattering [2–5]. These studies are along the same line with the coupled-channel dynamical models for the meson-baryon scattering studied in 60's, where the vector meson exchange interaction was adopted. This phenomenological interaction is now identified as the

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Weinberg-Tomozawa (WT) term, which is the leading order term in chiral perturbation theory. In this respect, one can introduce higher order corrections into the interaction systematically. The WT interaction was originally derived in current algebra. Since current algebra tells us about the interaction for arbitrary target hadrons, it is possible to apply the chiral unitary approach to the system with spin 3/2 baryons with the decuplet baryons as target, to the heavy quark sectors, and to the axial vector mesons. In the series of studies, the properties of the generated resonances are in fair agreement with experimental data.

On the other hand, the hadrons observed so far can be classified by their flavor quantum numbers. *Empirically*, there is a regularity in the quantum numbers of the observed hadrons: the states with the valence quark contents of $\bar{q}q$ or qqq were observed, while no state was well established with larger number of valence quarks (4, 5, 6, ... quarks). The latter states, called exotic hadrons, were intensively studied recently after the report on the Θ^+ by LEPs collaboration [6]. In spite of the large amount of theoretical works, it is not clear why the exotic hadrons are difficult to observe.

In order to clarify this issue, we have recently performed an analysis of exotic hadrons in s -wave chiral dynamics [7–10]. We utilize the framework of the chiral unitary approach, since it is naively expected that the resonances produced in the dynamical model should have large component of the multi-quark configuration, which is the flavor partner of the exotic hadrons in the s -wave scattering.

We construct the scattering amplitude of an arbitrary hadron with the Nambu-Goldstone boson $t(\sqrt{s})$ as

$$t(\sqrt{s}) \rightarrow V^{\text{chiral}}(\sqrt{s}) \quad \text{at low energy,} \quad (1)$$

$$\text{Im}t^{-1}(\sqrt{s}) = \frac{\rho(\sqrt{s})}{2}, \quad (2)$$

where $V^{\text{chiral}}(\sqrt{s})$ is the low energy interaction based on chiral symmetry and $\rho(\sqrt{s})$ is the phase space of the two-body scattering. Eq. (1) is the constraint from the chiral low energy theorem, whereas Eq. (2) guarantees the unitarity of the S-matrix. Utilizing this approach, we would like to study what chiral dynamics tells us about the existence of the exotic hadrons.

The low energy s -wave interaction of a target hadron (T) with the NG boson in a channel α is given by

$$V_\alpha = -\frac{\omega}{2f^2}C_{\alpha,T}, \quad (3)$$

where ω and f are the energy and the decay constant of the NG boson, and the expression for the group theoretical factor $C_{\alpha,T}$ is given in Refs. [7–10].

By examining the coupling strength $C_{\alpha,T}$ for exotic channels, we find that the interaction for exotic channels is in most cases repulsive, and the strength of the possible attractive interaction is uniquely determined as

$$C_{\text{exotic}} = 1. \quad (4)$$

Eqs. (3) and (4) determines the low energy interaction V_{chiral} in Eq. (1) for exotic channels.

Next we construct the scattering amplitude consistent with Eq. (2). Based on the N/D method [4], the general form of the scattering amplitude $t_{\alpha}(\sqrt{s})$ can be written down with one subtraction constant, which is determined by the requirement (1) at the scale $\sqrt{s} = M_T$ [8]. Thus we obtain the scattering amplitude $t_{\alpha}(\sqrt{s})$ which satisfies both Eqs. (1) and (2). We then search for poles of bound states in the amplitude $t_{\alpha}(\sqrt{s})$. From the energy dependence of the interaction and the loop function, we find the critical value for the attractive interaction strength which is enough to make a bound state as

$$C_{\text{crit}} = \frac{2f^2}{m[-G(M_T + m)]}, \quad (5)$$

where $G(\sqrt{s})$ is defined as once-subtracted dispersion integral [8]. If the interaction strength $C_{\alpha,T}$ is larger than this critical value, a bound state is generated in the amplitude. Comparing C_{crit} with the attractive interaction in the exotic channel (4), we show that the interaction is not strong enough to generate a bound state for the mass of the target hadron smaller than 6 GeV.

In this way, we have studied the exotic states in the NG boson-hadron scattering. We construct the scattering amplitude which satisfies the chiral low energy theorem and unitarity condition. Considering an arbitrary target hadron, we find that the interaction in the exotic channels are in most cases repulsive, and possible attractive interaction is uniquely given as $C_{\text{exotic}} = 1$. We show that the strength of the attractive interaction is not sufficient to generate a bound state for the physically known masses of the target hadrons.

In order to draw a general and model-independent conclusion, we have simplified the framework of the chiral unitary approach. Our basic assumptions are 1) flavor SU(3) symmetry and 2) dominance of the leading order interaction. Once we accept these conditions, the subsequent arguments are straightforward. In practice, however, the SU(3) symmetry is broken and the higher order terms of the chiral expansion would play a substantial role, especially for the NG boson with larger masses. These effects could be included in the kernel interaction based on chiral perturbation theory, but we need experimental data to determine the low energy constants. It should

be noted that the exotic hadrons constructed by other mechanisms than the present analysis, such as by quark dynamics, are not excluded.

In this study, we stress that the WT term is the leading order term of the chiral expansion and the strength is only determined by the group theoretical factor. We can therefore argue that the leading order term does not provide bound states in exotic channel, without performing experiments. Given the success of the chiral unitary approach in the nonexotic sectors which our arguments are based on, our result may partly explain the difficulty to observe exotic hadrons in nature.

Acknowledgements

T.H. appreciates Prof. W. Weise for the discussion about the convergence of chiral expansion. T. H. thanks the Japan Society for the Promotion of Science (JSPS) for financial support. This work is supported in part by the Grant for Scientific Research (No. 17959600, No. 19853500, No. 18042001, and No. 16540252) and by Grant-in-Aid for the 21st Century COE "Center for Diversity and Universality in Physics" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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